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INVESTIGATION OF AN AUTOMATED MATERIALS HANDLING SYSTEM USING A GPSS SIMULATION

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Final Report

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This is a report of an investigation of the validity of a conceptual automated material handling system with tool, machine, and transfer mechanism failures. The development of a modular GPSS simulation model is used to study and analyze the system. The modular design makes it a good basis for construction of more complex models of larger similar physical concepts. The larger models are easily generated through the use of "macros".

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FOREWORD

This research discussed in this report was accomplished as part of the Product/Production Engineering Graduate Program conducted by DARCOM Intern Training Center. As such, the ideas, concepts and results herein presented are those of the author and do not necessarily reflect approval or acceptance by the Department of the Army.

This report has been reviewed and is approved for release. For further information on this project contact: Dr. Herchel E. Lynch, DRXMC-ITC-PPE, Red River Army Depot, Texarkana, Texas 75501.

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ABSTRACT

This is a report of an investigation of the validity of a conceptual automated material handling system with tool, machine, and transfer mechanism failures. The development of a modular GPSS simulation model is used to study and analyze the system. The modular design makes it a good basis for construction of more complex models of larger similar physical concepts. The larger models are easily generated through the use of "macros".

Results of this study indicate the proposed material handling concept can operate effectively. Recommendations are given for further study of a more complex system.

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CHAPTER I

INTRODUCTION

New production line concepts are needed in manufacturing facilities in order to reach optimum production and safety levels. The United States Army Materiel Development and Readiness Command (DARCOM) is currently sponsoring an ammunition modernization program to improve ammunition production facilities. A projectile manufacturing facility is to be installed at an ammunition plant with a new, fully automated material handling concept. Since the production facility is not operational, this is a test of a concept. Among these are the number of machines per sub-system, the number of cradles per conveyor, input and output rates, machine operation times, conveyor speeds, failure probability distributions (MTBF), mean repair times (MTTR), and all measurable distances.

Controlled laboratory simulations of industrial situations are now possible. The systems analyst can learn quickly and at low cost the answers that would rarely be obtainable from manipulating the actual system.

This is a report of the analysis of a system which lends itself to digital computer simulation. It provides information on the validity of the material handling system and how it reacts to tool, machine, and transfer mechanism failures. Although the discussion here is

restricted to answering specific questions of a design concept, valuable information is given for larger and more complex systems.

The Production Line Sub-System

The production line can be divided into several sub-systems. Each sub-system's task may be different; however, the material handling system is generally the same for each. A sub-system consists of a two-tiered eliptical conveyor with a specified number of identical machines located between the two conveyors. (See Figure 1.1) An item or unit comes into a sub-system by a straight-line conveyor and is transferred to the top eliptical conveyor. The unit continues moving on this conveyor until a machine can accept it. (See Figure 1.2) At this time, the unit leaves the conveyor and enters a machine's finite waiting space. The machine accepts the unit, operates, and transfers it to the lower eliptical conveyor. (See Figure 1.1) Finally, the unit travels on this conveyor until it can move onto another straight-line conveyor, called a transfer mechanism, which transfers the unit to the next sub-system.

An eliptical conveyor, henceforth to be called a carousel, has a specific number of equally spaced cradles. These cradles are continuously moving and must be in line with a transfer point to accept or reject a unit.

Finite waiting spaces or buffer zones are located at input and output positions of each machine. These buffer

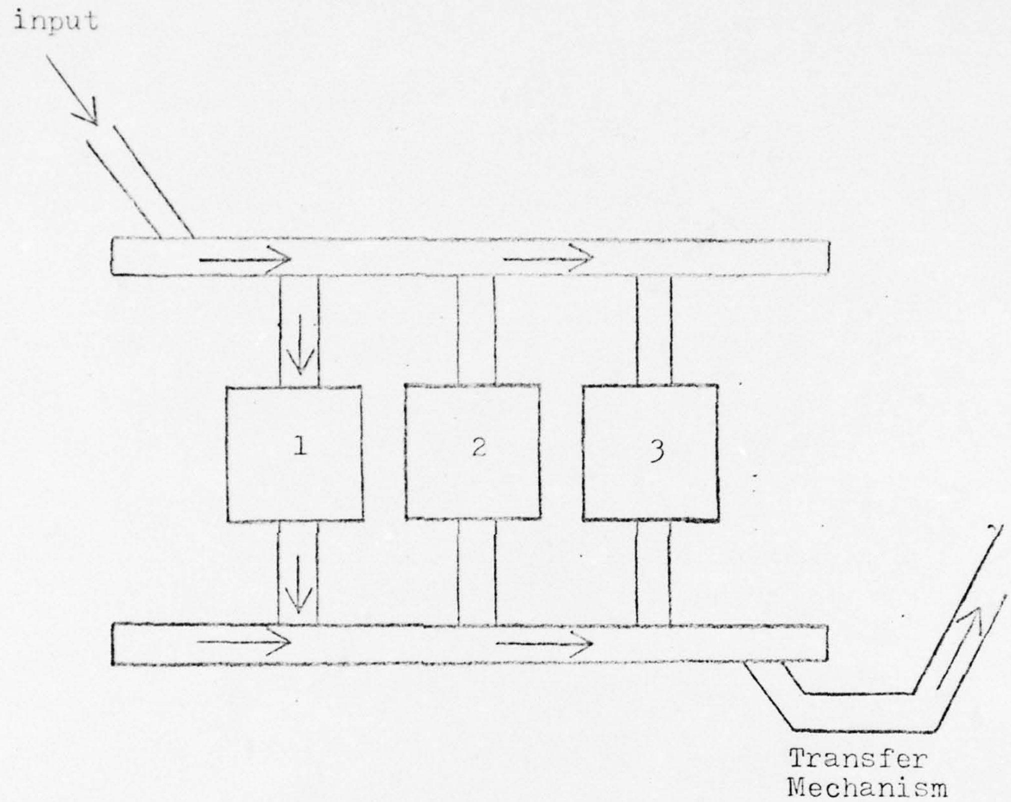


Figure 1.1 Two-Tiered Conveyor System with Machines
(Side View)

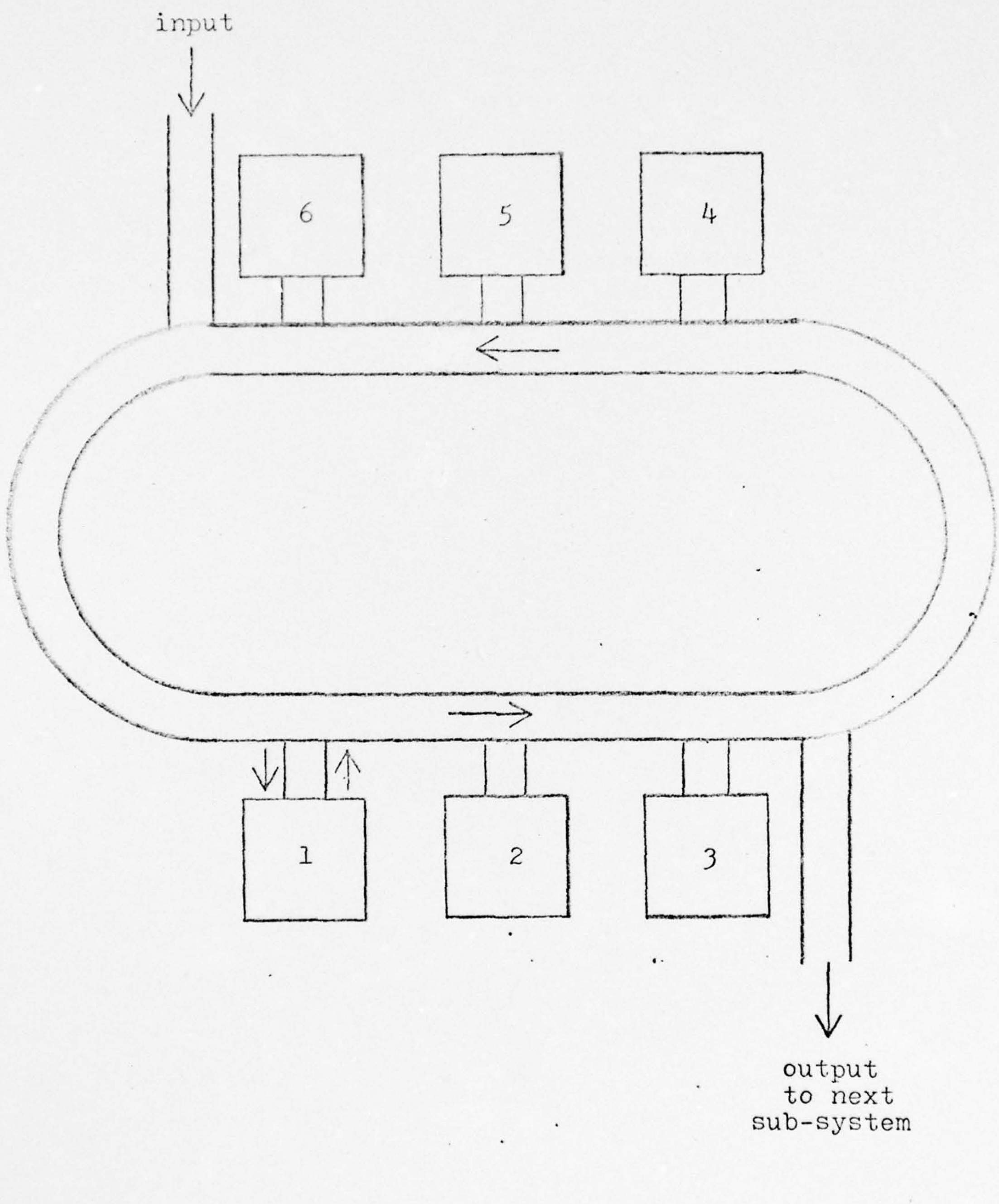


Figure 1.2 A Sub-System With 6 Machines

zones can be adjusted to hold from 1 to 5 units.

The transfer mechanism is a straight-line conveyor, which transfers a unit from one sub-system to the next sub-system at a constant speed. It has a discrete number of item spaces and is automatically controlled by switches. When the input queue to the next sub-system is filled, these switches enable the transfer mechanism to detour incoming units and stop moving.

All the necessary values and ideas were extracted from project reports and drawings in order to insure model validity. The mathematical relationships needed to simulate a proposed production line are given in Appendix A. The data used in the model is summarized in Table 1.1.

The Modeling Approach

Digital computer simulations have increased dramatically in recent years due to the decreasing cost and increasing speed of electronic computers, as well as, the improvements in problem-oriented simulation languages. Two of the major advantages are: (1) computer simulations allow study of the system without actual modification of that system and (2) the computer can manipulate elaborate descriptive models that consider complex interrelationships and simultaneously deal with a large number of individual units.

The GPSS programming language (IBM, 1970; Schriber, 1974) was used to develop this model. GPSS was chosen due

Table 1.1 Input Data

	Sub-System 1	Sub-System 2
Factual:		
Spacing Between Cradles on Carousel	8 inches	8 inches
Width of Carousel	12 feet	12 feet
Assumed:		
Number of Machines	6	10
Number of Cradles per Carousel	48	66
Input Rate	1 unit/sec	1 unit/sec
Machine Output Rate	600 parts/hr	360 parts/hr
Conveyor Speeds	1.125 ft/sec	1.0 ft/sec
Carousel Side's Length	96 inches	160 inches
Circumference of Carousel	54 feet	66 feet
Buffer Waiting Spaces	3	3
Distance Between Adjacent Machines	32 inches	32 inches
Transfer Mechanism's Maximum Queue Length = 10		
Number of Repairmen = 2		

to the problem's complexity, the language's local availability, and GPSS's unique features. Other widely used programming languages include SIMSCRIPT, FORTRAN, and GASP. However, using these languages for modeling complex systems require abnormally large programs. This usually results in a difficulty for an interested individual to understand the model logic.

The production line was simulated as two connecting sub-systems. (See Figure 1.3) This modular approach allows increasing or decreasing the size of the model and changing of any necessary input data. The output can be studied for the validity of the concept, system reactions to failures, and optimum maintenance scheduling procedures.

Literature Review

The increase in simulation and modeling is reflected in the literature of fields such as engineering, computer science, operations research, statistics, economics, and business administration. A search for information revealed no prior investigations concerning this engineering problem. GPSS programming language texts and manuals received the majority of attention. As mentioned earlier, two important references are the IBM User's Manual (IBM, 1970) and Schriber's "Simulation Using GPSS" (Schriber, 1974).

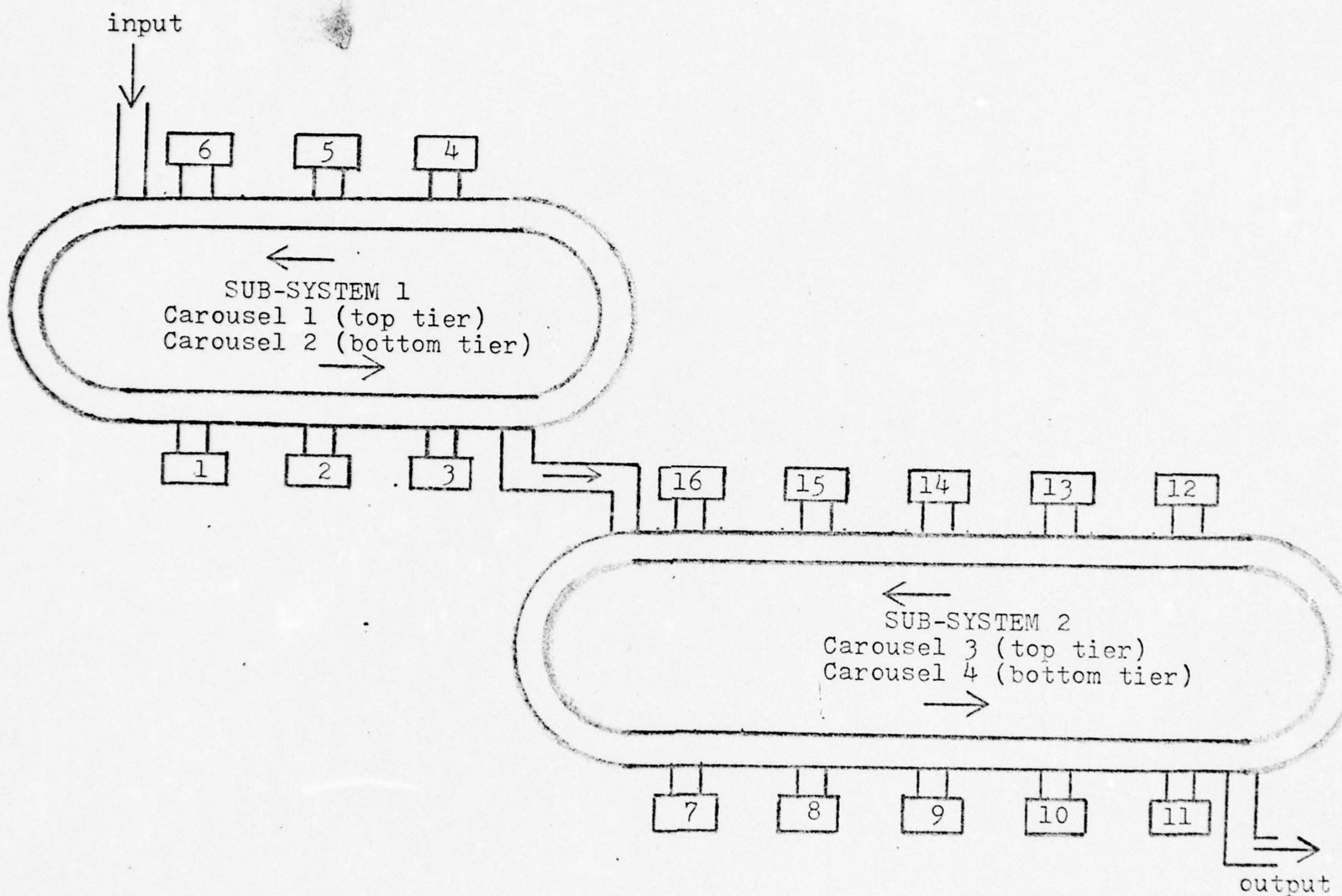


Figure 1.3 System ,To Be Simulated

CHAPTER II

THE MODEL

The task of interpreting the problem in the context of GPSS was approached by a logical description of the material handling system. Since sections of the model may be confusing, an explanation of the rationale behind the particular approach used is necessary.

Structure of the Model

The model is composed of a major model segment, and three supporting segments. In the major segment, Model Segment 1, the production line is simulated. Model Segment 2 controls the failures of the transfer mechanism. Whether the transfer mechanism is currently working is communicated to the major segment through a LOGIC SWITCH. In another supporting segment, Model Segment 3, machine failures are simulated. A PREEMPT Block transmits a machine failure to the major segment. The final supporting segment controls the duration of the run.

Developing GPSS representations for the production line presented many logic problems. Since it consists of two similar sub-systems, sub-system 1 required the main programming effort. Once this was accomplished, the task was simply to repeat a list of program statements with the necessary data for sub-system 2.

Each transaction represents a unit as it moves through

Model Segment 1. Ten parameters are defined for each transaction in order for the units to move in a fixed order and record movement data.

Model Logic

A transaction asks a series of questions while it waits on the input conveyor for a cradle on carousel 1:

> Which cradle is currently in front of
> the input conveyor?
> Is it vacant?
> Yes, move onto the cradle.
> No, wait for the next cradle.

To accomplish this in the model, a unit enters an ASSIGN Block where the cradle number currently in front of the input conveyor becomes the value of Parameter 1. The unit then arrives at a GATE Block controlled by a LOGIC SWITCH. If the cradle is vacant, the unit continues to the next block and puts the LOGIC SWITCH into the "Set" position, indicating the cradle is now occupied. If the cradle is occupied, the unit is sent through a counter, which increments the number waiting in the input queue and then leaves the model. This is made possible since the input rate is equal to the time it takes the next cradle to arrive at the input conveyor. The value of the Variable "SPAC1" is the cradle number currently in front of the input conveyor for each transaction:

$$\text{SPAC1} = \left[(\text{the number of transactions entered } -1)/48 \right] + 1$$

The brackets denote integral portion of a number. The input rate is equal to the time it takes the next cradle to

arrive at the input conveyor, thus, there is a one-to-one correspondence between the number of transactions which have entered the model and the needed cradle number.

Once a unit occupies a cradle, it travels on the carousel from one location to another. Transfer point positions on carousel 1 are at the input conveyor and the machines. To simulate the movement of the carousel, four GPSS Blocks are utilized. When a unit moves into the Block "ASSIGN 3,FN$TOA1", the time needed for the unit to reach the next position is copied into the value of Parameter 3. It is then held at an ADVANCE Block until the unit arrives at the specified location. After arriving at this location, the position number becomes the value of Parameter 2. If the transaction can enter the machine's finite waiting space, it leaves the carousel; if it can not enter, it moves to the next machine.

The Function "TOA1" describes the time needed for the unit to reach the next location. The data used in this function is calculated with the following equation:

$$Y_i = \frac{\text{distance to the next position}}{\text{conveyor speed of carousel 1}}$$

where Y_i is the travel time to the next location from location i.

Once a unit has passed through a machine, it waits in the exiting buffer zone for a cradle on carousel 2 and again asks a series of questions:

Which cradle is currently in front of
this exiting buffer zone?
Is it vacant?
Yes, move onto the cradle.
No, wait for the next cradle.

This is accomplished with the same block logic used while the unit waited on the input conveyor for a cradle on carousel 1. The value of the Variable "OUT1" is the cradle number currently in front of a machine's exiting buffer zone:

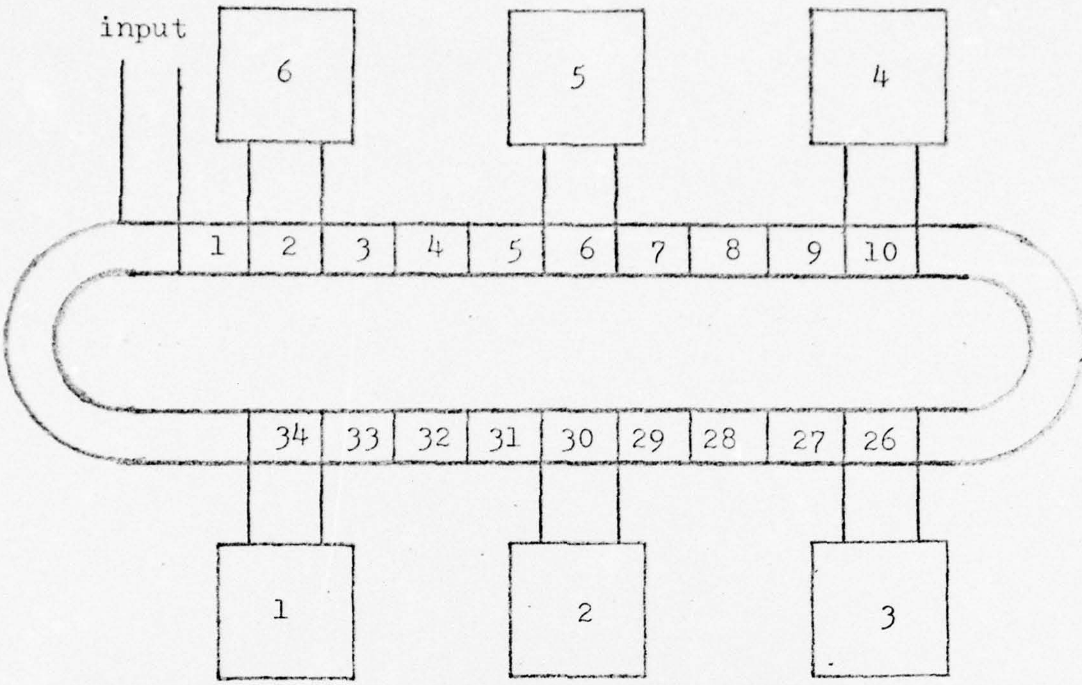
OUT1= [(the number of transactions entered - 1 + FOUT1)/48] +49

Notice the similarity between the equations for the Variables "OUT1" and "SPAC1" and the brackets again denote integral portion of their argument. The Function "FOUT1" is a tabular value which describes the number of cradles between the input conveyor and each machine. (See Figure 2.1) The constant 49 is added since the cradle numbers on carousel 2 range from 49 through 96.

Once a unit occupies a cradle, it travels on the carousel to the transfer mechanism. The Function "TOA2" describes the time needed for the unit to reach the transfer mechanism. If Z_i is the travel time to the transfer mechanism from location i, then

$$Z_i = \frac{\text{distance to the transfer mechanism}}{\text{conveyor speed of carousel 2}} .$$

The representation of the transfer mechanism is considerably simplified, since the operational characteristics are nonessential details. It is modeled as a finite



let: x_i = machine number

y_i = number of cradles between the input conveyor and machine i

Function "FOUT1"

x_i	y_i
1	34
2	30
3	26
4	10
5	6
6	2

Figure 2.1 Diagrammatic Representation of Function "FOUT1"

waiting area with a capacity of ten.

Finally, as units wait in an exiting buffer zone or the transfer mechanism for a cradle, only the unit in first place attempts to occupy a cradle. In order to stop all other units from trying to occupy a cradle, which would be unrealistic and a waste of computer time, LOGIC SWITCHES are used as holding gates.

Model Implementation

A small time increment of 0.1 second is used, due to the rapid movement of the units during the simulation. The selection of a larger time increment will cause considerable round-off errors, due to the nature of the available GPSS.

The model is run for 6 minutes, with no failures, to reach steady state conditions. The statistics are then reset to zero and a 12 minute run, with failures, is started. Inspection of the second START card shows that the card's Snap Interval Option and the signal for CHAIN Printouts have been used. The Snap Interval Option causes statistical printouts to occur after the 6th and 12th minutes of simulation. This makes it possible to trace the behavior of statistics. The CHAIN Printouts are not necessary; however, they give valuable information for debugging the program and tracing a unit's movement.

GPSS provides an efficient method of system simulation. The program was run on an IBM/360 and an AMDAHL/470. The

cost of each run ranged from \$7 to \$10. It also required an average of 196K of core for a simulation of twelve minutes real time.

Verification, Validity, or Merit?

The production line studied has not been constructed. While a rigorous verification of the model is impractical, the runs made indicate the model is sound.

CHAIN Printouts enable the analyst to understand the behavior of the model. Because events can occur simultaneously in this system, but are caused to occur sequentially in the GPSS model, the question of "what happens next" in GPSS is of the utmost importance. An explanation of "what happens next" is given in terms of chain concepts. Also, a study of the parameter values included in the CHAIN Printouts showed the movement of units through the system.

Four separate runs were made. The first run considered no failures. The second, third, and fourth runs considered tool, transfer mechanism, and machine failures, respectively. The similarity of the units behavior in the model to "real" systems for each run, implies the simulation has merit.

CHAPTER III

PROGRAM OUTPUT

Descriptions and interpretations of the program output are presented to assist in development of larger and more complex systems. A basic understanding of GPSS is assumed. Appendix C gives a listing of the various GPSS entities used in the model, with a brief explanation of their interpretation as elements in the material handling system.

A section of the FUTURE EVENTS CHAIN is shown in Table 3.1. Typical transaction parameter values appear in this printout. (An explanation of column labels in GPSS CHAIN printouts can be found in Appendix B.) For example, transaction 52 is residing in BLOCK number 55. (The Extended Program Listing in Appendix D indicates this is an ADVANCE Block in Model Segment 1.) This can be translated to say, transaction 52 is a unit on carousel 4 traveling to the transfer mechanism. The parameters P1, P2, ..., P10 are a record of the transaction's movement. Parameter 1(=89) indicates the unit captured cradle 89 on carousel 2. This raises the question of which cradle was used by this unit on carousel 1? Since the value of P1 is the cradle number a unit occupies on sub-system 1, the cradle number on carousel 1 is destructively replaced by the cradle number on carousel 2 as the unit travels through the

Table 3.1 FUTURE EVENTS CHAIN Printouts

FUTURE EVENTS CHAIN

TRANS	BDT	BLOCK	PR	SF	NBA	SET	MARK-TIME	P1	P2	P3	P4	SI	TI	DI	CI	MC	PC	PF
43	10801	8	1		9	43	10380	30	3	192	0					4		
								0	0	0	0							
								0	0	0	0							
23	10801	8	1		9	23	10620	6	0	181	0					4		
								0	0	0	0							
								0	0	0	0							
156	10801	37	1		38	156	9590	72	5	24	21					4		
								0	160	8	28							
								0	0	0	0							
68	10803	37	1		38	68	8630	72	5	24	21					4		
								0	130	12	28							
								0	0	0	0							
52	10805	55	1		56	52	7880	89	6	24	22					4		
								0	224	13	28							
								29	0	0	0							
59	10805	37	1		38	59	8330	90	5	24	21					4		
								0	100	16	218							
								0	0	0	0							
111	10805	55	1		56	111	9610	76	1	181	17					4		
								0	222	9	28							
								25	0	0	0							
120	10805	16	1		17	120	10130	5	5	24	0				1	4		
								0	0	0	0							
								0	0	0	0							
194	10805	8	1		9	194	10360	28	4	24	0					4		
								0	0	0	0							
								0	0	0	0							
60	10805	8	1		9	60	10600	4	1	24	0					4		
								0	0	0	0							
								0	0	0	0							
165	10807	37	1		38	165	9530	66	5	24	21					4		
								0	155	10	28							
								0	0	0	0							
49	10808	37	1		38	49	9050	66	5	24	21					4		
								0	127	13	28							
								0	0	0	0							
185	10808	79	2		80	185	9[illegible]0	95	6	24	22					4		
								0	119	0	0							
								0	0	0	0							
9	10809	8	1		9	9	10100	2	2	24	0					4		
								0	0	0	0							
								0	0	0	0							

sub-system. Parameter 2(=6) indicates transaction 52 entered machine 6's waiting space (from carousel 1). Parameter 3(=24) indicates the unit had traveled from its preceding position (machine 5) to machine 6 (on carousel 1) in 2.4 seconds (the time unit is 0.1 second). Parameter 4(=22) indicates the corresponding exiting buffer zone for machine 6 was number 22. Parameter 5(=0) indicates the unit did not need to use this exiting buffer zone's holding gate. When the unit reached sub-system 2, similar events were recorded in parameters P6,P7,...,P10. The unit captured cradle 224 on carousel 4. On carousel 3, it had traveled from its preceding position (machine 12) to machine 13 in 2.8 seconds. The corresponding exiting buffer zone for machine 13 was number 29. Finally, the unit did not need to use this exiting buffer zone's holding gate.

The INTERRUPT CHAIN is shown in Table 3.2(a). There is one transaction resident on the CHAIN. Transaction 71 is the unit (non-preemptive FACILITY user) which is as yet unfinished with the machine. It is known to be a non-preemptive user because its "Next Block Attempted" is Block 17 (the SAVEVALUE Block in Model Segment 1). The BDT ("Block Departure Time") column shows a value of 1. For each transaction on an INTERRUPT CHAIN, the BDT entry can be interpreted as its "remaining holding time" at the machine from which it has been displaced. Hence, a repairman (a preemptive machine user) has 1 time unit to go before he will

Table 3.2

(a) INTERRUPT CHAIN Statistics

INTERRUPT CHAIN TRANS	BDT	BLOCK	PR	SF	NBA	SET	MARK-TIME	P1	P2	P3	P4	SI	TI	DI	CI	MC	PC	PF
71	1		1		17	71	7360	16	2	24	0			1	1		1	
								0	0	0	0							
								0	0	0	0							

(b) FACILITY Statistics

FACILITY	AVERAGE UTILIZATION	NUMBER ENTRIES	AVERAGE TIME/TRAN	SEIZING TRANS. NO.	PREEMPTING TRANS. NO.
1	1.000	90	80.000	13	
2	1.000	46	156.521	71	69
3	1.000	98	73.469	190	
4	1.000	95	75.789	85	
5	1.000	91	79.120	120	
6	1.000	91	79.120	108	
7	.909	60	109.149	57	
8	.863	57	109.122	97	
9	.860	58	106.879	152	
10	.847	56	108.928	24	
11	.848	55	111.072	19	
12	.829	55	108.545	136	
13	.816	54	108.888	65	
14	1.000	18	400.000	157	
15	.816	59	99.677	99	
16	.760	56	97.767	72	

be finished repairing the machine. Note that the various column labels for the INTERRUPT CHAIN are identical to those for the FUTURE EVENTS CHAIN. This makes it possible to examine the parameter values. Parameter 2(=2) indicates machine 2 is currently being repaired.

Statistics describing the performance of the machines are shown in Table 3.2(b). The output for machine 2 will be discussed in detail. It shows the machine was busy 100% of the time, but does not distinguish between that part of the time operating, and that part spent being repaired when a unit is still in the machine. Under NUMBER ENTRIES, it is seen that the machine was captured by 46 units. Note the values of 71 and 69 which appear in the statistics under the SEIZING TRANS. NO. and PREEMPTING TRANS. NO. columns, respectively. This shows that transaction 71 is a displaced user of the machine, and transaction 69 is currently simulating a repair of the machine.

The listing of all LOGIC SWITCHES, currently in use, is shown in Table 3.3. The LOGIC SWITCHES listed for cradles represent the "occupied" cradles. Since LOGIC SWITCH 400 is in the "on" position, the holding gate in the transfer mechanism is presently being used.

The STORAGE statistics are shown in Table 3.4. For each STORAGE, seven different pieces of information are printed. Consider the output for STORAGE 110 whose capacity is the number of repairmen. The CAPACITY represents

Table 3.3 Listing of LOGIC SWITCHES

LOGIC SWITCH - SET (ON) STATUS

SWITCH	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	
	1	2	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
	34	35	36	37	38	40	41	42	43	44	46	47	48	53	54	55
	57	59	60	65	66	71	72	100	101	102	103	106	107	108	110	111
	112	113	114	117	118	119	127	130	135	136	137	139	140	145	146	147
	148	150	155	156	157	160	162	163	164	165	167	168	170	171	173	177
	178	180	181	183	187	188	190	197	198	222	223	224	226	227	400	

Table 3.4 STORAGE Statistics

STORAGE	CAPACITY	AVERAGE CONTENTS	AVERAGE UTILIZATION	ENTRIES	AVERAGE TIME/TRAN	CURRENT CONTENTS	MAXIMUM CONTENTS
1	3	2.930	.976	92	229.336	3	3
2	3	2.979	.993	47	456.510	3	3
3	3	2.909	.969	100	209.500	3	3
4	3	2.914	.971	97	216.371	3	3
5	3	2.815	.938	93	217.956	3	3
6	3	2.360	.786	93	182.752	3	3
7	3	2.456	.818	62	285.322	3	3
8	3	2.464	.821	59	300.745	3	3
9	3	2.462	.820	60	295.516	3	3
10	3	2.387	.795	58	296.396	3	3
11	3	2.380	.793	56	306.053	2	3
12	3	2.326	.775	57	293.842	3	3
13	3	2.213	.737	56	284.553	3	3
14	3	2.935	.978	19	1112.315	3	3
15	3	2.029	.676	61	239.540	3	3
16	3	1.668	.556	58	207.120	3	3
17	3	.384	.128	89	31.123		3
18	3	.529	.176	44	86.590		3
19	3	.368	.122	97	27.319		3
20	3	.491	.163	94	37.659		3
21	3	.516	.172	90	41.333		3
22	3	.533	.177	90	42.666		3
23	3	.048	.016	59	5.932		1
24	3	.029	.009	56	3.750		1
25	3	.031	.010	57	4.035		1
26	3	.087	.029	55	11.454		1
27	3	.000	.000	54	.000		1
28	3	.000	.000	54	.000		1
29	3	.000	.000	53	.000		1
30	3	.000	.000	16	.000		1
31	3	.000	.000	58	.000		1
32	3	.000	.000	55	.000		1
100	10	1.443	.144	510	20.378	1	8
110	2	1.364	.682	3	3274.000	1	2

the two repairmen assigned to the system during the simulation. These repairmen were busy only 68.2% of the time. Under ENTRIES, it is seen that a repairman was needed on three different occasions for an AVERAGE TIME of 327.4 seconds. Currently, one repairman is being utilized, however, both repairmen were needed simultaneously at least once during the simulation.

The SAVEVALUE information is shown in Table 3.5(a). Note the value of SAVEVALUE 100 is 201. This can be interpreted as the number of units which have been backed-up downstream due to the failures in the system being studied.

Table 3.5(b) is the statistics of the behavior of the QUEUE in the model called TRANS. Currently, no units are waiting for open cradles on carousel 3, however, there were as many as 7 units in the waiting line besides the unit trying to capture a cradle during the simulation.

Table 3.5

(a) SAVEVALUE Statistics

CONTENTS OF HALFWORD SAVEVALUES (NON-ZERO)

SAVEVALUE	NR,	VALUE	NR,	VALUE	NR,	VALUE	NR,	VALUE	NR,	VALUE	NR,	VALUE	NR,	VALUE	NR,	VALUE
	1	3	2	36	3	80	4	77	5	66	6	59	7	26	8	12
	9	5	10	19	11	7	12	9	13	7	14	35	15	73	16	74
	100	201	200	1080												

(b) QUEUE Statistics

QUEUE	MAXIMUM CONTENTS	AVERAGE CONTENTS	TOTAL ENTRIES	ZERO ENTRIES	PERCENT ZEROS	AVERAGE TIME/TRANS	$AVERAGE TIME/TRANS	TABLE NUMBER	CURRENT CONTENTS
TRANS	7	.868	415	282	67.9	15.062	47.000		

$AVERAGE TIME/TRANS = AVERAGE TIME/TRANS EXCLUDING ZERO ENTRIES

CHAPTER IV

RECOMMENDATIONS

The model has been written to enable a person to increase the size of a sub-system, increase the number of sub-systems, and change any data necessary. If core limitations and cost restrict the size of the system, it appears that an adequate representation of the material handling system can still be obtained. First, increase the number of connecting sub-systems to only four or five. Second, run the simulation for an eight hour day. If these restrictions are not used, relatively expensive computer resources will be needed.

Three types of failures were incorporated into the model: tool, machine, and transfer mechanism. The addition of carousel failures will give a complete representation of all major failures. These failures were ignored in this investigation due to their infrequency and the extensive computer programming needed to simulate them. The model contained in this report will cost approximately $500 to simulate an eight hour day. One carousel failure may occur in this time period and it would simply stop all output and fill all the buffers before the failure point.

In this model, Block sequences are used repetitively with different variables. A certain amount of keypunching

effort can be spared if the Block sequences are defined by macros, with dummy variables supplied in the various Operand positions. The Processor will then substitute these Blocks at various points in the model. A single MACRO card is used at each of these different points to indicate that the macro Block sequence is to be inserted and the dummy variables are to be replaced with the actual variables specified.

From this preliminary study, it can be said the proposed material handling system can operate effectively. However, further study is suggested with the acquisition of additional information for a more complex system. This should give a basis for definitive statements on the system's reactions to failures and an optimum maintenance scheduling policy. It is important to remember, a simulation does not yield a "solution" to the problem as a mathematical model yields an analytical solution; instead it permits a less abstract and relatively more faithful representation of a real system.

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Discusses application of the Monte Carlo method to deterministic problems in mathematics, distribution sampling in mathematical statistics, and digital systems simulation in management science and economics.

Shannon, E. "Simulation: A Survey with Research Suggestions," AIIE Transactions, Vol. 7, No. 3, September 1975.
This paper attempts to survey selected aspects of simulation and point out areas needing additional research. Among the topics discussed are programming languages, starting conditions, and validation.

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This is a large volume that is very well done. Chapter 2 has an excellent discussion of GPSS CHAIN features.

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An excellent paper which addresses the question of what are the major characteristics of the empirical aspects of validation and how one might carry out such a validation process for complex computer system models.

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APPENDIXES

Appendix A	Mathematical Relationships
Appendix B	Explanation of Column Lables in GPSS CHAIN Printouts
Appendix C	Table of Definitions
Appendix D	Extended Program Listing

Input Rate[1] (I)	Sub-System 1			Sub-System 2		
	Conveyor Angular Velocity (V)	Conveyor Speed (S)	Max Machine Operation Time (MOT)	Conveyor Angular Velocity (V)	Conveyor Speed (S)	Max Machine Operation Time (MOT)
1.1 $\frac{units}{sec}$	.0231 $\frac{rev}{sec}$	1.250 $\frac{ft}{sec}$	5.4 $\frac{sec}{item}$	.0167 $\frac{rev}{sec}$	1.102 $\frac{ft}{sec}$	9.1 $\frac{sec}{item}$
1.0	.0208	1.125	6.0	.0152	1.000	10.0
.9	.0189	1.023	6.6	.0136	.900	11.1

(1) An Input Rate of 1.0 units/sec was used in the simulation

APPENDIX A

MATHEMATICAL RELATIONSHIPS

$$V = (I/N)(1 \text{ cradle/item})$$

$$S = (C)(V)$$

$$MOT = M/I$$

where:

C = circumference of carousel
N = number of cradles on carousel
M = number of machines

For Sub-System 1:	For Sub-System 2:
C = 54 ft/rev N = 48 cradles M = 6	C = 66 ft/rev N = 66 cradles M = 10
V = (I/48 cradles)(1 cradle/item)	V = (I/66 cradles)(1 cradle/item)
S = (54 ft/rev)(V)	S = (66 ft/rev)(V)
MOT = 6/I	MOT = 10/I

MATHEMATICAL RELATIONSHIPS (CONTINUED)

APPENDIX B

EXPLANATION OF COLUMN LABELS IN GPSS CHAIN PRINTOUTS

TRANS	Transaction number j.
BDT	Block Departure Time. This represents either the absolute clock time at which the transaction is scheduled to leave an ADVANCE Block (FUTURE EVENT CHAIN) or the time at which it last left an ADVANCE Block (any other CHAIN).
BLOCK	The number of the block at which the transaction is currently located.
PR	Priority Level of Transaction (0,1,...,127).
SF	Selection Factor. Indicates the type of next block trial to be made. (blank)=indicates only one next block to be tried. B=indicates that the current block (given in the BLOCK column) is a TRANSFER Block with a BOTH selection mode. A=indicates that the current block is a TRANSFER Block with an ALL selection mode. The NBA column lists the lowest of the n next blocks to be tried.
NBA	Next Block Attempted. The next block to be entered by the transaction.
SET	Assembly Set Linkage. When the transaction is created, the set number is equal to the transaction number itself. A linkage is formed whenever the transaction enters a SPLIT Block. This linkage is updated when any member of an assembly set enters a SPLIT or TERMINATE Block.
MARK TIME	Mark Time is the time at which a transaction moved out of its GENERATE Block into the model.
P1,...,P4 P5,...,P8 ...	The first line of printout for each transaction lists the current value of Parameter 1 through 4. The second line lists the values of Parameters 5 through 8 where P5 is in the P1 column, P6 is in the P2 column, etc.

SI	Scan Status Indicator. A one indicates that a next block trial is to be suppressed until the condition causing the delay changes.
TI	Tracing Indicator. A one indicates that the transaction has entered a TRACE Block. It is reset to zero by an UNTRACE Block.
DI	Delay Indicator. A one indicates that the transaction has failed to move directly into some next block. It is used with the TRANSFER Block in the SIM selection mode which resets the delay indicator. The indicator is also reset when the transaction leaves an ADVANCE Block where a nonzero delay time is computed.
CI	Chain Indicator. Zero indicates transaction is in Matching Status or on a User's Chain. One indicates the transaction is in an Interrupt Status. Two indicates the transaction is in CURRENT EVENTS CHAIN. Four indicates the transaction is in FUTURE EVENTS CHAIN.
MC	Matching Condition. A four indicates that the transaction is available for MATCHing, or is at an ASSEMBLE or GATHER Block in the process of being assembled or gathered; otherwise the column is blank.
PC	Preempt Count. This field is incremented by one whenever the transaction is PREEMPTed at one of the facilities which it has SEIZEd or PREEMPTed. It is decremented by one whenever the preempt condition is removed.
PF	Preempt Flag. A one indicates that the transaction is to be PREEMPTed when it enters the next ADVANCE Block that specifies a nonzero time. The transaction will also be PREEMPTed if it is delayed at a MATCH, GATHER, or ASSEMBLE Block. The indicator is reset to zero when the transaction is PREEMPTed.

(Taken From IBM's General Purpose Simulation System/360 Introductory User's Manual)

APPENDIX C

TABLE OF DEFINITIONS

Time Unit: 0.1 seconds

GPSS Entity	Interpretation
Transactions	
Model Segment 1	The flow of items through the production line. P1,P2,...,P5 correspond to items on sub-system 1. P6,P7,...,P10 correspond to items on sub-system 2. P1: The cradle number item wants to (or does) occupy P2: The machine number where the item is located; P2 value of zero corresponds to the position of the input conveyor P3: The time needed for the item to reach the next position on carousel 1 P4: The corresponding exiting buffer zone for each machine P5: The corresponding holding gate for each exiting buffer zone P6: Same as P1 P7: The machine number where the item is located P8: The time needed for the item to reach the next position on carousel 3 P9: Same as P4 P10: Same as P5
Model Segment 2	A potential transfer mechanism failure
Model Segment 3	Potential machine failures P1: The number of the machine which has failed
Model Segment 4	The timer

GPSS Entity	Interpretation
Functions	
FFAIL	A Function describing the tool failure probability distribution; a failure occurs after a varying number of tool operations
FOUT1	A Function describing the addition factor needed to calculate the cradle number a unit wants to occupy when the unit is leaving a machine and trying to capture a cradle on output carousel 2
FOUT2	Same as FOUT1, except unit is trying to capture a cradle on output carousel 4
MFAIL	A Function describing the machine failure probability distribution.
POS1	A Function describing the position (machine number) the unit is currently located (on carousel 1)
POS2	A Function describing the position (machine number) the unit is currently located (on carousel 3)
TOA1	A Function describing the time needed for the unit to reach the next position on carousel 1
TOA2	A Function describing the time needed for the unit to reach the transfer mechanism on carousel 2
TOA3	A Function describing the time needed for the unit to reach the next position on carousel 3
TOA4	A Function describing the time needed for the unit to reach the output transfer mechanism on carousel 4

GPSS Entity	Interpretation
Facilities	
1,2,...,6	The machines on sub-system 1
7,8,...,16	The machines on sub-system 2
Logic Switches	
1,2,...,48	The Logic Switches simulating the "occupied"-"vacant" condition of the cradles on carousel 1
49,50,...,96	The Logic Switches simulating the "occupied"-"vacant" condition of the cradles on carousel 2
97,98,...,162	The Logic Switches simulating the "occupied"-"vacant" condition of the cradles on carousel 3
163,164,...,228	The Logic Switches simulating the "occupied"-"vacant" condition of the cradles on carousel 4
301,302,...,316	Logic Switches 301,302,...,316 simulate the corresponding holding gates for machine 1,2,...,16's exiting buffer zones
399	The Logic Switch, when Set, indicates that the transfer mechanism is not operating
400	The Logic Switch simulating the holding gate in the transfer mechanism
Queues	
TRANS	The waiting line in the transfer mechanism in which units wait for open cradles on carousel 3

GPSS Entity	Interpretation
Savevalues	
1,2,...,16	Savevalues in which are stored the number of machine operations for machine 1,2,...,16, respectively
100	Savevalue in which is stored the number of units waiting downstream
200	Savevalue in which is stored the number of units that have entered the model
Storages	
1,2,...,16	Storages whose capacities are the finite waiting spaces in the entering buffer zones of machines 1,2,...,16, respectively
17,18,...,32	Storages whose capacities are the finite waiting spaces in the exiting buffer zones of machines 1,2,...,16, respectively
100	Storage whose capacity is the finite waiting spaces in the transfer mechanism
110	Storage whose capacity is the number of repairmen
Variables	
HOLD1	A variable whose value is the holding gate number used in exiting buffers on sub-system 1
HOLD2	A variable whose value is the holding gate number used in exiting buffers on sub-system 2
OUT1	A variable whose value is the cradle number a unit tries to occupy on carousel 2 when leaving a machine

GPSS Entity	Interpretation
OUT2	A variable whose value is the cradle number a unit tries to occupy on carousel 4 when leaving a machine
SPAC1	A variable whose value is the cradle number a unit tries to occupy on carousel 1 when entering the model
SPAC2	A variable whose value is the cradle number a unit tries to occupy on carousel 3 when leaving the transfer mechanism
XBUF1	A variable whose value is the exiting buffer zone a unit is occupying on sub-system 1
XBUF2	A variable whose value is the exiting buffer zone a unit is occupying on sub-system 2

APPENDIX D

EXTENDED PROGRAM LISTING

Required Job Control Language:

```
// JOB T  1001                              RON        TAMU 600 J
// XEQ BOOTS
//SIM105 JOB (S976,RRAD,001,002,RR),'ROSENTHAL'
/*PASSWORD
/*JOBPARM REGION=256
// EXEC GPSS,REGION=256K,TIME=(,10)
//DINPUT1 DD *
```

```
BLOCK
NUMBER  *LOC   OPERATION  A,B,C,D,E,F,G              COMMENTS
               SIMULATE
        *
        *      FUNCTION DEFINITIONS
        *
         FFAIL FUNCTION    RN1,C2          TOOL FAILURE FUNCTION
        0,72/1,86
         FOUT1 FUNCTION    P2,L6           ADDITION FACTOR FOR OUTPUT CAROUSEL 2
        1,34/2,30/3,26/4,10/5,6/6,2
         FOUT2 FUNCTION    P7,D10          ADDITION FACTOR FOR OUTPUT CAROUSEL 4
        7,51/8,47/9,43/10,39/11,35/12,18/13,14/14,10/15,6/16,2
         MFAIL FUNCTION    RN1,C2          MACHINE FAILURE FUNCTION
        0,1/1,17
         POS1  FUNCTION    P2,D7           POSITION OF ARRIVAL FOR CAROUSEL 1
        0,1/1,2/2,3/3,4/4,5/5,6/6,1
         POS2  FUNCTION    P7,D11          POSITION OF ARRIVAL FOR CAROUSEL 3
        6,7/7,8/8,9/9,10/10,11/11,12/12,13/13,14/14,15/15,16/16,7
         TOA1  FUNCTION    P2,D7           TOA TO NEXT POSITION ON CAROUSEL 1
        0,181/1,24/2,24/3,192/4,24/5,24/6,192
         TOA2  FUNCTION    P2,L6           TOA TO OUTPUT CONVEYOR ON CAROUSEL 2
        1,59/2,36/3,12/4,299/5,276/6,252
         TOA3  FUNCTION    P7,D11          TOA TO NEXT POSITION ON CAROUSEL 3
        6,204/7,28/8,28/9,28/10,28/11,218/12,28/13,28/14,28/15,28/16,218
         TOA4  FUNCTION    P7,D10          TOA TO OUTPUT CONVEYOR ON CAROUSEL 4
        7,120/8,93/9,67/10,40/11,13/12,443/13,417/14,390/15,363/16,337
        *
        *      VARIABLE DEFINITIONS
        *
         OUT1  VARIABLE    ((XH200-1)+FN$FOUT1) 48+49
         OUT2  VARIABLE    ((XH200-1)+FN$FOUT2) 66+163
         SPAC1 VARIABLE    (XH200-1) 48+1
         SPAC2 VARIABLE    (XH200-1) 66+97
         XBUF1 VARIABLE    P2+16           EXITING BUFFER ZONES FOR CAROUSEL 2
         XBUF2 VARIABLE    P7+16           EXITING BUFFER ZONES FOR CAROUSEL 4
         HOLD1 VARIABLE    P2+300          HOLDING GATE BUFFERS FOR XBUF1
         HOLD2 VARIABLE    P7+300          HOLDING GATE BUFFERS FOR XBUF4
        *
        *      SAVEVALUE INITIALIZATIONS FOR RANDOM TOOL FAILURES
        *
               INITIAL     XH1,10/XH2,13/XH3,7/XH4,10/XH5,1/XH6,3
               INITIAL     XH7,14/XH8,4/XH9,1/XH10,13/XH11,7/XH12,11
               INITIAL     XH13,13/XH14,3/XH15,1/XH16,10
        *
        *      STORAGE CAPACITY DEFINITIONS
        *
               STORAGE     S1-S32,3/S100,10/S110,2
        *
        *      MODEL SEGMENT 1             THE PRODUCTION LINE
        *
1              GENERATE    10,,,,3         UNITS COME INTO SYSTEM VIA INPUT CONVEYOR
2              SAVEVALUE   200+,1,H        INCREMENT NO. OF TRANSACTIONS ENTERED
3              PRIORITY    1               DECREASE PRIORITY
4        TRY1  ASSIGN      1,V$SPAC1       P1=  OF CRADLE ON CAROUSEL UNIT WANTS
5              GATE LR     P1,WAIT1        IS CRADLE AVAILABLE ON CAROUSEL
6              LOGIC S     P1              CAPTURE CRADLE ON CAROUSEL
7        NEXT1 ASSIGN      3,FN$TOA1       P3=TOA TO NEXT POSITION
```

```
         ADVANCE    P3            MOVE TO NEXT POSITION
         ASSIGN     2,FN$POS1     P2=POSITION OF ARRIVAL
         TRANSFER   BOTH,STOR1,NEXT1 SEE IF UNIT CAN ENTER BUFFER
STOR1    ENTER      P2            ENTER BUFFER ZONE OF MACHINE
         LOGIC R    P1            EMPTY CRADLE ON CAROUSEL
         SEIZE      P2            CAPTURE MACHINE
         LEAVE      P2            LEAVE BUFFER
         TEST LE    XH*2,FN$FFAIL,TFAL1     HAS MACHINE TOOL FAILED
MACH1    ADVANCE    60            MACHINE OPERATES
         SAVEVALUE  P2+,1,H       COUNT MACHINE OPERATIONS
         ASSIGN     4,V$XBUF1     P4=CORRESPONDING EXITING BUFFER ZONE
         ENTER      P4            ENTER EXITING BUFFER ZONE
         RELEASE    P2            RELEASE MACHINE
TRY2     ASSIGN     1,V$OUT1      P1=  OF CRADLE ON CAROUSEL UNIT WANTS
         GATE LR    P1,WAIT2      IS CRADLE AVAILABLE ON CAROUSEL 2
         PRIORITY   1             DECREASE PRIORITY IF NEEDED
         LOGIC S    P1            CAPTURE CRADLE ON CAROUSEL
         LEAVE      P4            LEAVE EXITING BUFFER ZONE
         ADVANCE    FN$TOA2       MOVE TO TRANSFER MECHANISM
CAR2     GATE LR    399,NOGO1     IS TRANSFER CONVEYOR WORKING
         TRANSFER   BOTH,TRANS,NOGO1    SEE IF UNIT CAN ENTER TRANSFER MECH
TRANS    ENTER      100           ENTER TRANSFER MECHANISM
         LOGIC R    P1            RELEASE CRADLE ON CAROUSEL 2
TRY3     ASSIGN     6,V$SPAC2     P6=  OF CRADLE ON CAROUSEL UNIT WANTS
         GATE LR    P6,WAIT3      IS CRADLE AVAILABLE ON CAROUSEL
         PRIORITY   1             DECREASE PRIORITY IF NEEDED
         LOGIC S    P6            CAPTURE CRADLE ON CAROUSEL
         LEAVE      100           LEAVE TRANSFER MECHANISM
NEXT2    ASSIGN     8,FN$TOA3     P8=TOA TO NEXT POSITION
         ADVANCE    P8            MOVE TO NEXT POSITION
         ASSIGN     7,FN$POS2     P7=POSITION OF ARRIVAL
         TRANSFER   BOTH,STOR2,NEXT2 SEE IF UNIT CAN ENTER BUFFER
STOR2    ENTER      P7            ENTER BUFFER ZONE OF MACHINE
         LOGIC R    P6            EMPTY CRADLE ON CAROUSEL
         SEIZE      P7            CAPTURE MACHINE
         LEAVE      P7            LEAVE BUFFER
         TEST LE    XH*7,FN$FFAIL,TFAL2     HAS MACHINE TOOL FAILED
MACH2    ADVANCE    100           MACHINE OPERATES
         SAVEVALUE  P7+,1,H       COUNT MACHINE OPERATIONS
         ASSIGN     9,V$XBUF2     P9=CORRESPONDING EXITING BUFFER ZONE
         ENTER      P9            ENTER EXITING BUFFER ZONE
         RELEASE    P7            RELEASE MACHINE
TRY4     ASSIGN     6,V$OUT2      P6=  OF CRADLE ON CAROUSEL UNIT WANTS
         GATE LR    P6,WAIT4      IS CRADLE AVAILABLE ON CAROUSEL  4
         PRIORITY   1             DECREASE PRIORITY IF NEEDED
         LOGIC S    P6            CAPTURE CRADLE ON CAROUSEL
         LEAVE      P9            LEAVE EXITING BUFFER ZONE
         ADVANCE    FN$TOA4       MOVE TO TRANSFER MECHANISM
         LOGIC R    P6            RELEASE CRADLE ON CAROUSEL 4
OUT      TERMINATE
NOGO1    ADVANCE    480           GO AROUND AGAIN
         TRANSFER   ,CAR2         TRY AGAIN
TFAL1    ADVANCE    600,100       REPAIR TOOL
         SAVEVALUE  P2,0,H        RESET NO. OF MACHINE OPERATIONS TO 0
         TRANSFER   ,MACH1        GO BACK TO RUN
TFAL2    ADVANCE    600,100       REPAIR TOOL
         SAVEVALUE  P7,0,H        RESET NO. OF MACHINE OPERATIONS TO 0
```

```
65           TRANSFER   ,MACH2       GO BACK TO RUN
66     WAIT1 SAVEVALUE  100+,1,H     INCREMENT NO. WAITING DOWNSTREAM
67           TRANSFER   ,OUT         LEAVE MODEL
68     WAIT2 ASSIGN     5,V$HOLD1    P5=HOLDING GATE FOR OTHER UNITS IN BUFFER
69           GATE LR    P5           IS UNIT FIRST ON LINE
70           LOGIC S    P5           CAPTURE FIRST PLACE
71           ADVANCE    10           WAIT TILL NEXT CRADLE
72           PRIORITY   2            INCREASE PRIORITY
73           LOGIC R    P5           OPEN FIRST PLACE POSITION
74           TRANSFER   ,TRY2        TRY AGAIN
75     WAIT3 QUEUE      TRANS        ENTER LINE
76           GATE LR    400          IS UNIT FIRST ON LINE
77           DEPART     TRANS        LEAVE LINE
78           LOGIC S    400          CAPTURE FIRST PLACE
79           ADVANCE    10           WAIT TILL NEXT CRADLE
80           PRIORITY   2            INCREASE PRIORITY
81           LOGIC R    400          OPEN FIRST PLACE POSITION
82           TRANSFER   ,TRY3        TRY AGAIN
83     WAIT4 ASSIGN     10,V$HOLD2   P10=HOLDING GATE FOR OTHER UNITS IN BUFFER
84           GATE LR    P10          IS UNIT FIRST ON LINE
85           LOGIC S    P10          CAPTURE FIRST PLACE
86           ADVANCE    10           WAIT TILL NEXT CRADLE
87           PRIORITY   2            INCREASE PRIORITY
88           LOGIC R    P10          OPEN FIRST PLACE POSITION
89           TRANSFER   ,TRY4        TRY AGAIN
     *
     *       MODEL SEGMENT 2         TRANSFER MECHANISM FAILURE
     *
90           GENERATE   3900,,,1,3
91           LOGIC S    399          TRANSFER CONVEYOR FAILS
92           ENTER      110          CAPTURE A REPAIRMAN
93           ADVANCE    1200,100     REPAIR IT
94           LOGIC R    399          WORK AGAIN
95           LEAVE      110          FREE THE REPAIRMAN
96           TERMINATE
     *
     *       MODEL SEGMENT 3         MACHINE FAILURES
     *
97           GENERATE   3900,,,,3    MACHINE FAILS
98           ASSIGN     1,FN$MFAIL   P1=NO. OF MACHINE WHICH FAILED
99           PREEMPT    P1           TAKE MACHINE OUT OF PRODUCTION
100          ENTER      110          CAPTURE A REPAIRMAN
101          ADVANCE    6000,600     MACHINE IS BEING REPAIRED
102          RETURN     P1           MACHINE GOES INTO PRODUCTION
103          LEAVE      110          FREE THE REPAIRMAN
104          TERMINATE
     *
     *       MODEL SEGMENT 4         THE TIMER
     *
105          GENERATE   3600         TIMER ARRIVES AFTER 6 MINS
106          TERMINATE  1
             START      1,NP         START STEADY STATE RUN
             RESET
             START      2,,1,1       RUN FOR 12 MINS
             END        RETURN CONTROL
```